460-RQMT-0042

Orbit Design Requirements

for

MMS

March 26, 2001

An unofficial document (ie, unsigned) compiled by C Petruzzo using inputs from the STDT 12/1999 report and from the MMS Study team members.

Initial Comments

This document was written by the orbit designers who will develop candidate trajectories for the MMS mission. The trajectories we produce must satisfy certain requirements. This is a statement of our understanding of the trajectory requirements for MMS. <u>If it's not in this document, it's not a trajectory requirement.</u>.

People designing the MMS elements, us included, need details, not generalities. Unfortunately, requirements for research missions surface slowly, sometimes being defined only when their absense halts or misdirects progress. MMS is in its early stages, so some requirements are considered firm, others are known to exist but with insufficient detail to be useful, and still others are unknown. In this document, the firm ones are stated as such (but don't count on them not changing anyway) and those lacking detail or representing guesses are identified. Those that have not surfaced are waiting until their need becomes apparent.

The key to designing the mission lies in the requirement concerning apogee as it passes through local midnight in phase 2. From there, a potential candidate reference trajectory can be propagated backward to launch and forward to the end of the mission, being accepted or rejected as the other requirements are satisfied or violated. The requirement is stated in the phase 2 section.

Whether there will phases 3 and 4 is undecided at this writing.

At the end of this document is a history of how the requirements have changed since the original version of this document.

Definitions

A "requirement" imposes conditions on the trajectories. Any trajectory that satisfies all requirements is acceptable. Otherwise, it is not acceptable. There is no in-between.

A "given" is a statement accepted as fact and used in designing acceptable trajectories.

"Firmness" indicates the degree of certainty about the given or requirement. The given or requirement will be used as stated even if it is just a guess on the part of whomever supplied it.

"TBS" represents information unknown at this writing.

"Comment" is incidental information.

"Source" is the document and/or person supplying the information.

References and Sources

Document: Magnetospheric Multi-Scale Mission Spacecraft Requirements (**TBS** date); available via the "library" button on the MMS web page http://mms.gsfc.nasa.gov/.

Document: Magnetospheric Multi-Scale Mission... Resolving Fundamental Processes in Space Plasmas, a report of the NASA Science and Technology Definition Team, December 1999.

Acronyms

S/C	Spacecraft
GSE	Geocentric Solar Ecliptic
GSM	Geocentric Solar Magnetic
MMS	Magnetospheric MultiScale
STDT	Science and Technology Definition Team
IRAS	Interspacecraft Ranging and Alarm System

General Requirements

G.1) Given: The mission duration is at most 26 months, starting at launch.

Source: Mary DiJoseph, verbally, 1/8/2001

Firmness: Uncertain. The Announcement of Opportunity will(?) say this is a 24 month mission. It has not been verified that spacecraft checkout, boom deployment, etc, is in addition to the 24 months is included in it.

G.2) Given: There are 4 satellites in the MMS set.

Source: S/C Requirements document, current on 10/11/00

Firmness: Firm

G.3) Given: The magnetosphere model to be used in determining the region in which the spacecraft lies at any moment is the one used by GSFC's Satellite Situation Center (SSC). The SSC web page address is http://sscweb.gsfc.nasa.gov/.

Source: SteveCurtis; verbally, 10/11/00

Firmness: Firm

Comment: the phase 1 requirements include one involving a model of the magnetopause; that model is independent of the one above.

Comment: the phase 2requirements include one involving a model of the neutral sheet; that model is independent of the one above.

G.4) Given: The mission consists of one engineering phase and two *(or four)* science phases. The engineering phase, phase 0, is the period between launch and phase 1, the start of science operations. Definitions for the science phases are given later in this document.

Source: Announcement of Opportunity, expected summer 2001

Firmness: that there will be at least two science phases is firm; whether there will be an additional two is uncertain.

G.5) Given: A reference satellite following a reference orbit will be defined by the orbit designers. One refers to it when discussing matters related to the satellites as a group.

Source: Al Lieberman; verbally, 10/11/00

Firmness: Firm

G.6) Given: A quality factor will be used to describe the regularity of the formation at a given time. How it is applied is specific to the mission phase and is addressed later in this document. The formation quality factor is defined as follows:

The quality, Q, of the tetrahedron formed by the MMS spacecraft at any instant equals the ratio of the actual tetrahedron volume to the volume of an ideal one. The ideal tetrahedron is equilateral, with edge length equal to the mean of the edge lengths of the actual tetrahedron.

Source: Jim Slavin, verbally, 1/8/2001.

Firmness: That there will be a quality factor is firm; whether the one stated will be retained is uncertain.

G.7) Given: When determining the delta-v needed for an orbit control maneuver, assume that the available thrust is in the spin plane and along the spin axis in both directions. The in-plane thrust is either radially through the spin axis or the result of two tangential thrusters firing simultaneously so as to produce the equivalent of a radial thruster.

Source: Al Lieberman and Shane Hynes; verbally, 10/06/00

Firmness: The thrust directions are assumed temporarily until the spacecraft design has been completed.

G.8) Given: Throughout the mission, the spin axis of each satellite will be almost normal to the ecliptic. It will be offset to within 5 degrees of normal, with one possible exception. The exception is that for orbit control maneuvers the spin axis may be reoriented up to **TBS** degrees from the ecliptic near-normal attitude. Reorientation is permitted when the cost of aligning the spin axis with the delta-v vector, applying the delta-v using the axial thruster(s), and returning to the ecliptic near-normal attitude is less than the cost of not doing so.

The cost of reorienting the spacecraft, as a delta-v equivalent, is **TBS** m/s per degree of reorientation before the wire booms have been deployed and **TBS** m/s after.

The offset's magnitude and direction from ecliptic normal define the ecliptic near-normal attitude but are not expected to be known in the forseeable future. Computations will be done as though the offset were zero.

Sources: S/C Requirements document, for the near-normal statement, current on 10/11/00
TBS, for the reorientation permission
TBS, for the delta-v equivalents

Firmness: Whether reorienting the spin axis will be allowed is uncertain; having a sun-aligned spin axis instead of an ecliptic normal one is under investigtion.

Comment: The "spin axis" is a line with no positive or negative sense. It is used instead of "spin vector" to avoid matters involving the direction of spin and whether the "top" of the spacecraft is toward the north or south ecliptic pole.

Comment: The size of the reorientation is limited for power and thermal considerations.

G.9) Requirement: For each orbit control maneuver, the delta-v expended shall be the lesser of the two described in the statement immediately above. If the delta-v's are within **TBS** m/s of each other, no reorientation will be done.

Source: Al Lieberman and Shane Hynes

Firmness: Whether reorienting the spin axis will be allowed is uncertain; if allowed, the closeness test for delta-v will be applied; the closeness value is a judgement call and may change.

Comment: Delta-v consumption is the sum of the magnitudes of the axial and radial components individually.

Comment: The implication is that some maneuvers might be preceeded and followed by a reorientation, others might not.

G.10) Requirement: The total delta-v for orbit control shall not exceed 900 m/s for a two phase mission *(1100 m/s for a four phase one)*. Contingency, orbit correction, rotational, and other losses are not included.

Source: Al Liberman, Mary DiJoseph; verbally, 10/11/00

Firmness: That there is an upper limit is certain; its value is uncertain

Comment: This is subject to refinement as the mission design matures. The limits stated here is the total anticipated capability and leaves no room for attitude control, spin control, or contingency. In other words, the limits here are clearly too high but at least they're an upper bound.

G.11) Given: The maximum permissible perigee altitude in phases 0, 1, and 2 is 1.2 earth radii.

Source: Steve Curtis, verbally, 12/4/00

Firmness: Uncertain

Comment: This limits the radiation dosage.

G.12) Requirement: The perigee altitude for the reference orbit and for any satellite at any time during the mission shall be greater than 800 km. If necessary to prevent a violation, an orbit control maneuver shall be executed to raise the perigee altitude by an amount sufficient to eliminate the need for another maneuver, but not higher than the maximum stated above.

Source: Al Liberman and Shane Hynes; verbally, 10/06/00

Firmness: That there is a minimum altitude is firm; the minimum altitude value is a judgement call and could change.

Comment: If the perigee altitude that would eliminate the need for further perigee raisings exceeds the maximum allowed, multiple perigee raising maneuvers will be necessary.

Comment: There is no requirement regarding when perigee may be raised. This allows it to be raised whenever it has least impact on the science operations.

Comment: If the maneuer duration is found to be excessively long, the maneuver may have to be executed in segments over multiple orbits.

G.13) Requirement: Eclipses for the reference orbit and for any satellite at any time during the mission shall not exceed two hours. If necessary to prevent a violation, an orbit control maneuver shall be executed to change the trajectory by an amount sufficient to eliminate the need for another maneuver.

Source: S/C Requirements document (eclipse duration)

Firmness: That eclipse durations may be at least two hours long is firm; whether a longer duration is possible cannot be determined until the s/c design is complete.

Comment: The maximum eclipse duration is derived from thermal and power subsystem requirements.

Comment: If the maneuer duration is found to be excessively long, the maneuver may have to be executed in segments over multiple orbits.

G.14) Potential Given (retained from draft versions for possible use in the future): For satellite-to-satellite communications (i.e., via IRAS), the elevation of any satellite above or below the spin plane of any other satellite is +/- **TBS** degrees and the maximum distance is **TBS** km.

Source: IRAS study report, expected 1/01

Firmness: Whether there will be an IRAS is uncertain; if there is an IRAS, that there will be limitations is firm; what those limitations are would be obtained from a design document.

G.15) Potential Requirement (not a requirement, but retained from draft versions for possible use in the future): Satellite-to-satellite communications (i.e., via IRAS) must be possible (a) throughout all orbit control maneuvers and (b) whenever the satellite is in the neighborhood of apogee as defined in the sections of this document dealing with phases 1 and 2 ***(TBS** in phases 3 and 4)*. Except for these times, there is no requirement.

Source: Al Liberman, for the "during maneuvers" part; verbally, 10/11/00
Steve Curtis, for the neighborhood of apogee part; verbally, 10/11/00

Firmness: whether there will be an IRAS is uncertain; if there is an IRAS, the statement is firm

Comment: item (b) may be too restrictive; if it causes too many candidate trajectories to be eliminated, it will have to be reconsidered.

G.16) Given: Uplink and downlink considerations impose no requirements on the orbit design.

Source: Al Liberman and Shane Hynes; verbally, 10/06/00; Gary Meyers; verbally, 10/11/00

Firmness: Firm

G.17) Requirement: the orbit design shall accommodate the need to avoid collision of the satellites after they have separated from the stack. The minimum spacing from **TBS** minutes after separation until the end of the mission is **TBS** km.

Source: Al Liberman and Shane Hynes

Firmness: That there will be such a requirement is firm; what it will say is uncertain.

Phase 0 Requirements

0.1) Given: Launch will be no earlier than June 1, 2007

Source: Mary DiJoseph; verbally, 12/4/00

Firmness: Firm

0.2) Given: Phase 0 begins when the spacecraft stack separates from the launch vehicle. It lasts 60 days.

Source: Mary DiJoseph, verbally, 1/8/2001

Firmness: Uncertain

0.3) Given: The launch vehicle is the Delta 2925H-10. The reference orbit conditions are those of the spacecraft stack when it separates from the launch vehicle. The orbit conditions, including dispersions, are

Apogee radius (e.r.)	12.0+/-1.0	equals the phase 1 requirement;
Perigee radius (e.r.)	1.2	any value between the minimum and maximum is permitted; the minimum and maximum are given in the general requirements section
Inclination (deg)	28.7	inclination errors will not be corrected
Argument of perigee(deg)	any	most will be eliminated because they lead to excessive delta-v ; "any" is used until refinements are available
Longitude of the ascending node (deg)	**TBS**	
True Anomaly (deg)	**TBS**	

Source: **TBS** (the source should be a separate memo on Delta capability and assumed s/c mass)

Firmness: The apogee radius range and inclination are firm; the others are subject to change as the MMS mass estimate is refined and launch vehicle capability information becomes available

0.4) Given: the spacecraft will separate from their stack **TBS** (when?)

Source: Al Liberman and Shane Hynes

Firmness: That there will be such a given is firm; what it will state is uncertain

0.5) Requirement: 7 days after launch, the inclination of the reference orbit shall be changed to satisfy the phase 1 science requirements regarding inclination.

Source: Mary DiJoseph, 1/8/2001

Firmness: That there will be an inclination change is firm; when the inclination change will occur is uncertain.

Comment: This requirement will be refined as the mission design matures. A possible scenario would involve three maneuvers. The first would be a calibration burn, the next would bring the total to about 95% of what is planned, the third would complete the set.

0.6) Given: There are no formation requirements that must be satisfied for phase 0 purposes. What formation considerations exist in phase 0 are related to the phase 1 requirements. Spacing the satellites to avoid collision is not a formation issue.

Source: Al Liberman and Shane Hynes; verbally, 10/06/00

Firmness: Firm

0.7) Requirement: the orbits of the individual satellites shall be adjusted so that the formation requirements for phase 1 are satisfied when phase 1 begins. Those requirements are addressed in the next section of this document.

Source: Al Liberman and Shane Hynes; verbally, 10/06/00

Firmness: Firm

0.8) Given: Phase 0 ends when Phase 1 begins.

Source: Al Liberman and Shane Hynes; verbally, 10/06/00

Firmness: Firm

Phase 1 Requirements

1.1) Given: Phase 1 begins when the GSE local time of the reference orbit apogee is 03:40.

Source: Steve Curtis; verbally, 10/11/00

Firmness: Firm

Comment: The local time is as given in the 12/99 STDT report, page 27, section 5.1.

Comment: The requirement is independent of whether the mission has 2 or 4 science phases.

1.2) Requirement: The reference orbit apogee for phase 1 shall be between 11.0 and 13.0 earth radii. The perigee radius is unimportant, except that it must satisfy the minimum altitude requirement given in the general requirements section earlier in this document.

Source: Steve Curtis; verbally, 10/11/00

Firmness: Firm

Comment: The requirement does not obligate the orbit designer to deliver trajectories that blanket that range, only that what is delivered is within that range.

Comment: The statement about perigee being unimportant means that it can be adjusted to satisfy other requirements, within the limits of launch vehicle's capability.

1.3) Requirement: The reference orbit inclination for phase 1 shall be 10 degrees.

Source: STDT report, section 5.0; reaffirmed at STDT meeting, 8/31/00

Firmness: weak

Comment: perturbations cause significant changes in the inclination and controlling it would be prohibitively costly in propellant. The requirement would be better left unspecified so that science and engineering requirements could be used to eliminate unsuitable inclinations.

1.4) Requirement: Where a satellite following the MMS reference trajectory intersects the dayside magnetopause is a major factor in determining its acceptability. To be acceptable, the trajectory must be such that when apogee is in the sunward half of the GSE coordinate system, the GSM latitude of the intersections is between +/–30 degrees. The intersection will be determined using the mean magnetopause model defined in the paper identified below. The model is of the form $r = r_0 \left(2/(1+\cos(\theta)) \right)^{\alpha}$, with $r_0=10.0$ and $\alpha=0.6$.

Shue, Russell, and Song: "Shape of the Low-latitude Magnetopause: Comparison of Models", obtained from http://www-ssc.igpp.ucla.edu/personnel/russell/papers/shape_low/
Originally published in: Adv. Space Res., 25(7/8), 1271-1484, 2000

Source: Steve Curtis and Jim Slavin, model ok via email, 1/23/01
Constants by Jim Slavin, verbally, 2/2/01

Firmness: Firm, except for whether to apply this to all intersections in the sunward half

Comment: Compliance will be demonstrated in an xy plot of the crossing location GSM latitude versus GSE local time.

1.5) Requirement: the trajectory shall evolve into one that satisfies the phase 2 apogee local time requirement given in the Phase 2 section of this document.

Source: Steve Curtis; verbally, 10/11/00

Firmness: Firm

1.6) Given: For phase 1, the neighborhood of apogee is defined as that part of the trajectory where the distance from the earth center to the spacecraft is greater than 6 earth radii.

Source: Steve Curtis; verbally, 10/11/00

Firmness: Uncertain

1.7) Requirement: The time-average of the tetrahedron quality factor is must exceed **TBS** when computed over the neighborhood of apogee.

Source: Steve Curtis, Jim Slavin, verbally

Firmness: Uncertain

Comment: The quality factor is as defined in the general requirements section earlier in this document.

1.8) Requirement: In phase 1, the tetrahedron scale size is as in the following table. Whenever the formation quality factor requirement must be satisfied, the maximum and minimum separations between any two satellites during one orbital period shall be as in the table. The scale size is linear between the local times in the table.

Apogee GSE Local Time	Tetrahedron Scale Size (km)
03.40	100
24:00	10
18:00	100
12:00	10
06:00	100

Source: Steve Curtis, 1/8/2001

Firmness: Uncertain; the STDT 12/99 report indicates that the scale size can be as large as 0.1 earth radii (about 640 km).

Comment: The tetrahedron is equilateral when it is initialized, but decays from one orbit to the next. The scale size is the separation between one satellite and another at initialization.

1.9) Given: Phase 1 ends when the GSE local time of the reference orbit apogee reaches 06:00, after having passed through 24:00, 18:00, and 12:00.

Source: Steve Curtis; verbally, 10/11/00

Firmness: Firm

Comment: The 12/99 STDT report, page 27, does not state a local time explicitely.

Phase 2 Requirements

2.1) Given: Phase 2 begins when Phase 1 ends.

Source: Steve Curtis; verbally, 10/11/00

Firmness: Firm

2.2) Requirement: During the early part of Phase 2, the apogee radius shall be raised in stages from its Phase 1 value to 30 +/- 3 e.r. During the apogee raising parth of this phase, apogee shall be maintained in the dawnside magnetopause if possible or as near to it in the dawnside magnetosheath as fuel efficiency allows. The total fuel expended shall not exceed what would be expended if apogee were raised in a single orbit maneiver.

Source: Steve Curtis; verbally, 1/8/2001

Firmness: Raising apogee to the stated value is firm; expending no more fuel than what a single maneuver would cost is uncertain.

Comment: Because the GSE coordinate system rotates to keep the sun on the x axis, the GSE local time of apogee will decrease from its 06:00 value at the beginning of Phase 2 and will pass through midnight on its way toward the dusk side of the GSE coordinate system.

2.3 Given: A key quantity of interest is the dwell time within 3 Re of the neutral sheet, accumulated by a satellite following the MMS reference orbit. The dwell time is accumulated when the GSE local time of the satellite's instantaneous position is between 2200 to 0200 (includes midnight), and the distance from the earth is greater than **TBS** earth radii. The neutral sheet model is defined in

Fairfield, D. H., A Statistical Determination of the Shape and Position of the Geomagnetic Neutral Sheet, *Journal of Geophysical Research, Vol 85, No. A2, pages 775-780,* February 1, 1980

Source: Steve Curtis and Jim Slavin, verbally, 1/17/00

Firmness: Firm

Comment: This is a given instead of a requirement because, at this writing, the dwell time for a minimally acceptable trajectory has not been determined. Orbit design personnel will compute the dwell time for candidate trajectories that have not been rejected for other reasons. The acceptability of the dwell times will be assessed by the science team and the trajectories retained or rejected by them.

Comment: Compliance will be demonstrated by displaying the spacecraft trajectory in a two dimensional graph with distance from the neutral sheet in the GSM Z direction on the vertical axis and the GSM X coordinate on the horizontal axis.

Steve,Jim.... My hunch is that you want to infer something about dwell time (or some other quantity) from the above plot. If so, perhaps a useful plot would be one where the X quantity is the perpendicular distance to the neutral sheet and the Y quantity is the total time the satellite lies within X earth radii of the neutral sheet. This is less busy than the orbit trace plot, directly related to dwell time, and might be easier to use when comparing one trajectory with another.

2.4) Given: For phase 2, the neighborhood of apogee is defined as that part of the trajectory where the distance from the earth center to the spacecraft is greater than 6 earth radii.

Source: Steve Curtis; verbally, 10/11/00

Firmness: Uncertain

2.5) Requirement: The formation must have an acceptable quality factor whenever the reference satellite is in the neighborhood of apogee. The quality factor is defined as acceptable **TBS** *(how?.)* Otherwise it is unacceptable.

Source: **TBS**

Firmness: Uncertain

Comment: The quality factor is as defined in the general requirements section earlier in this document.

2.6) Requirement: In phase 2, the tetrahedron scale size is as in the following table. Whenever the formation quality factor requirement must be satisfied, the maximum and minimum separations between any two satellites during one orbital period shall be as in the table. The scale size is linear between the initial and final times in the table.

Apogee Location	Initial Scale Size (km)	Final Scale Size (km)
In/above the dawnside magnetopause	100	1000
Between the dawnside magnetopause and the center of the plasma sheet	1000	10
At the center of the plasma sheet	10	10

After passing the center of the plasma sheet, the tetrahedron size is allowed to change as perturbations dictate. Orbit maneuvers will be executed, if propulsion resources permit, to maintain the tetrahedron quality factor **TBS (how to say it?)**

Source: Steve Curtis, verbally 1/17/2001

Firmness: Uncertain

2.7) Given: For a mission with phases 0,1, and 2 only, Phase 2 ends when the GSE local time of the reference orbit apogee reaches 20:00.

Source: Steve Curtis; verbally, 1/8/2001

Firmness: Uncertain

Phase 3 Requirements

TBS, if there is a phase 3.

Phase 4 Requirements

TBS, if there is a phase 4.

Disposal of Satellites

D.1) Given: A disposal plan for each of the spacecraft will be developed.

Source: NASA Program Directive (NPD) 8710.3 or its successor.

Firmness: Firm

D.2) Requirement: The spacecraft disposal plan is **TBS**

History of Requirements Changes

Original Version: 3/26/2001; author: Charles Petruzzo, Goddard Space Flight Center

Updated Version: (....)